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NOLC REPORT 638

BROAD-BAND VLF TRANSMITTING TERMINATED DIPOLE

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RESEARCH DEPARTMENT

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FOREWORD

The work described in this report was performed during FY 1966 under the sponsorship of the Defense Communications Agency, MIPR No. 43-4-104, Job Order 455601, and the Office of Naval Research (Code 418), Purchase Order 6-0081.

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ABSTRACT

The need is cited for an efficient, easily constructed broad-band VLF transmitting antenna for ionospheric and other research. A multiconductor horizontal dipole is investigated experimentally and theoretically. The radiated E-field equations are derived for the terminated dipole, and field-strength measurements made out to 1400 km confirm the equations. Two such dipoles (a 5-conductor over soil of 16 mmho/m conductivity, and another with 10 conductors over a lava bed of 0.8 mmho/m conductivity) were constructed in the California desert. Measurements made yielded design data: impedance measurements to obtain propagation constants, bandwidth, attenuation per unit length, and mutual and characteristic impedances. Methods of improving efficiency of the horizontal dipole are discussed.

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7 March 1966

ERRATA

NOLC Report 638, BROAD-BAND VLF TRANSMITTING TERMINATED DIPOLE, by E. W. Seeley, Research Department, Naval Ordnance Laboratory, Corona, California, 7 February 1966.

Use pen and ink to make the following corrections.

Page	Correction
Abstract.	In sixth line, change "5-conductor" to read "10-conductor."
	In seventh line, change "10 conductors" to read "5 conductors."
5, LAVA-BED ANTENNA	In second line, change "0.8Ʊ/m" to read "0.8 mmho/m."
8, MULTIPLE CONDUCTORS . .	Change third sentence to read "Measurements of the radiated field strength of five conductors at 123 km range showed that the efficiency was five times that of the single conductor, with t' same input power."

INTRODUCTION

An efficient, easily constructed broad-band VLF antenna is needed for (1) ionospheric physics research; (2) VLF propagation studies such as vertical and oblique sounding of the ionosphere, where it is important to transmit, nearly simultaneously, frequencies across the VLF band; (3) world-wide communication; and (4) world-wide time standard.

There are, at present, no very efficient broad-band VLF antennas; the most efficient are the Navy communications antennas. These are large, top-loaded monopoles, which at best are 50 percent efficient, have a very narrow (0.4 percent) bandwidth, and cost approximately $100 million each. Obviously, the cost places such antennas out of reach of the low-budget experimenter.

This report discusses a horizontal dipole antenna that is easily constructed and can be made very broad-band and moderately efficient. Some experiments performed with an antenna of this type are described in subsequent paragraphs.

RADIATED FIELDS

The field radiated by a conductor in free space, with uniform current distribution along its incremental length, is

$$E_h = j\frac{60\pi(I\ell)}{R\lambda}\sin\phi \qquad (1)$$

where

E_h = horizontally polarized E-field

I = antenna current

ℓ = unit length

R = range

λ = wavelength

ϕ = angle from conductor axis

With the conductor brought down to a practical operating height, the radiated field must be modified by the earth's reflection coefficient.[1] In the elevation plane

$$E_h = j\frac{60\pi}{R\lambda}(I\ell)\left(\frac{2U}{U + \sin\phi}\right)\sin\phi \qquad (2)$$

where

$$U = \sqrt{\frac{\omega\epsilon_o}{j\sigma}}$$

in which ϵ_o is the dielectric constant of free space and σ is the conductivity of the soil.

For an antenna of finite length the propagation constants of the conductor over earth must be considered. The incremental current moment $I\ell$ is summed over the antenna length, L, by

$$(IL) = -I_{in}\left[\frac{e^{-\alpha L} e^{-j(\beta_1 - \beta\cos\phi)L} - 1}{\alpha + j\left(\beta_1 - \beta\cos\phi\right)}\right] \qquad (3)$$

where

α = antenna attenuation

$\beta = \frac{2\pi}{\lambda}$ free-space phase constant

$\beta_1 = \frac{2\pi}{(v/c)\lambda}$ antenna phase constant

In the term

$$\beta_1 = \frac{2\pi}{(v/c)\lambda}$$

v = wave velocity along antenna

c = wave velocity in free space

[1] Golden, R. M., R. S. MacMillan, and W. V. T. Rusch, "A VLF Antenna for Generating a Horizontally Polarized Radiation Field," Technical Report No. 2, Contract AF 18(600)1552, California Institute of Technology (10 July 1957). Wait, J. R., "The Electromagnetic Fields of a Horizontal Dipole in the Presence of a Conducting Half-Space," Can. J. Phys., Vol. 39 (1961), pp. 1017-28.

Therefore

$$E_h = -j\frac{120\pi I_{in} U \sin\phi}{R\lambda(U + \sin\phi)}\left[\frac{e^{-\alpha L} e^{-j(\beta_1 - \beta\cos\phi)L} - 1}{\alpha + j\left(\beta_1 - \beta\cos\phi\right)}\right] \tag{4}$$

is the radiated field in the elevation plane from a conductor over the ground, end-fed, and terminated in its characteristic impedance.

A dipole may be formed with two such conductors laid in opposite directions from the feed point. An extra term must be added to Eq. 4 for the radiated field

$$E_h = -j\frac{120\pi I_{in} U \sin\phi}{R\lambda(U + \sin\phi)}\left[\frac{e^{-\alpha L} e^{-j(\beta_1 - \beta\cos\phi)L} - 1}{\alpha + j\left(\beta_1 - \beta\cos\phi\right)} + \frac{e^{-\alpha L} e^{-j(\beta_1 + \beta\cos\phi)L} - 1}{\alpha + j\left(\beta_1 + \beta\cos\phi\right)}\right] \tag{5}$$

This horizontally polarized radiated field, commonly called the sky wave, is zero in the horizontal plane. The vertically polarized ground wave present in the horizontal plane can be derived in a similar manner; however, the reflection coefficient term is just $2U$ in the case of the ground wave and maximum radiation is off the end of the conductor.

Therefore, the radiated field for an end-fed antenna is

$$E_v = -j\frac{120\pi I_{in} U}{R\lambda}\cos\theta\left[\frac{e^{-\alpha L} e^{-jL(\beta_1 - \beta\cos\theta)} - 1}{\alpha + j\left(\beta_1 - \beta\cos\theta\right)}\right] \tag{6}$$

For a dipole terminated in its characteristic impedance the ground-wave field is

$$E_v = -j\frac{120\pi I_{in} U \cos\theta}{R\lambda}\left[\frac{e^{-\alpha L} e^{-jL(\beta_1 - \beta\cos\theta)} - 1}{\alpha + j\left(\beta_1 - \beta\cos\theta\right)} + \frac{e^{-\alpha L} e^{-jL(\beta_1 + \beta\cos\theta)}}{\alpha + j\left(\beta_1 + \beta\cos\theta\right)}\right] \tag{7}$$

ANTENNA PATTERNS

The above equations were programmed for the computer and several patterns, normalized to $120\pi I/R$, were computed for specific antennas. Figure 1 shows the shape of the elevation pattern of a terminated dipole 10 km in length that will be constructed on the Island of Hawaii for long-range propagation measurements. Figure 2 gives the azimuth pattern of that antenna, and Table 1 lists its propagation constants.

TABLE 1. Propagation Constants for Island Dipole

f(kc)	σ(℧/m)	$\frac{v}{c}$
10	0.4×10^{-3}	0.6
20	0.43×10^{-3}	0.6
30	0.50×10^{-3}	0.6

The elevation and azimuth patterns of an end-fed dipole antenna laid on a lava bed in the California desert are given in Figs. 3 and 4, respectively. Table 2 contains the measured propagation constants and soil conductivity.

TABLE 2. Propagation Constants for Desert Dipole

f(kc)	σ(℧/m)	$\frac{v}{c}$
10.9	0.8×10^{-3}	0.72
20.6	0.9×10^{-3}	0.73
32.7	1.0×10^{-3}	0.76

FIELD-SITE ANTENNA

When study of the problem of radiating VLF was first begun, measurements were made on a short dipole (2 km long) lying on the ground near the California desert NOLC field site. Impedance and radiation measurements were made to determine certain parameters of horizontal dipoles located on or near the ground. In general, the efficiency was found to be very low—on the order of a few thousandths of a percent—compared with that of a perfect monopole, but the efficiency was increased about 10 times when 10 dipoles were laid parallel. Mutual impedance between conductors tends to reduce the overall antenna efficiency. Mutual impedance measurements indicated only a few ohms when the dipoles were about 100 ft apart (Fig. 5).

The grounded antenna propagation constants were determined to be approximately 5 percent loss/km, and v/c of 0.5; the latter increased to 0.63 when the antenna was elevated 6 in. The characteristic impedance for a single-conductor antenna was approximately 300 Ω when lying on the ground; because of low mutual impedance Z_m, the impedance decreased linearly when additional dipoles were connected in parallel. The ground conductivity σ was determined to be 16 mmho/m, which is disadvantageous for the horizontal dipole.

LAVA-BED ANTENNA

Conductivity measurements were made on a lava bed 15 mi. north of the NOLC field site and the σ was 20 times lower (0.8 ℧/m) than at the field site. A five-conductor antenna 4.4 km long was constructed on the lava bed. Mutual-impedance measurements were made and it was determined that the conductors should be placed 500 ft apart to minimize mutual impedance to a few ohms/km.

Impedance measurements over the VLF band gave the propagation constants needed to compute the radiated field patterns. The characteristic impedance was about 320 Ω when the conductor was on the lava and 500 Ω when it was elevated 4 ft. The wave velocity along the antenna was 0.43c when the antenna was down, and 0.74c when elevated.

Current attenuation along the elevated antenna was determined to be approximately 50 percent less than when it was lying on the ground (see Fig. 6).

Radiated field strengths during daylight hours were measured off the end of the antenna at approximately 100 km intervals to a total range of 1400 km (Fig. 7). The signals were measured at the maximum range of 1400 km by using an audio-amplifier driver applying 300 w into the antenna. The usual interference between the ground wave and sky wave that causes a null at 200-300 km range is changed somewhat by the sky wave leaning toward the horizon at the higher VLF frequencies. A deep interference null at 300 km is evident in the 10.9 kc propagation curve; at the 20.6 and 32.7 kc frequencies, the nulls have been displaced to a higher range.

The equations derived earlier in this report were used to compute the ground-wave field strength at 43 km range, where the ground wave was predominant. It is noted from Table 3 that the computed values are in close agreement with the measured values.

TABLE 3. Radiated Field Strength of Lava-Bed Antenna

Antenna Radiation	f(kc)	Theoretical (μv/m)	Measured (μv/m)
Ground Wave (43 km range)	10.9	60	68.6
	20.6	139	148
	32.7	248	220
Sky Wave (1400 km range)	10.9	1.76	1.3
	20.6	3.96	4.0
	32.7	6.96	2.0

The sky-wave field strengths at 1400 km range were computed; as might be expected, the equations do not hold for great distances. However, close agreement exists between theoretical and measured field strengths at the lower range of VLF frequencies, but not at the higher.

In Table 4, the field strengths of four antennas, including the lava-bed dipole, are compared with those of a perfect quarter-wave monopole to determine the comparative efficiency of the lava-bed dipole. The power radiated by a perfect $\lambda/4$ monopole is

$$P_r = \left(\frac{E_v R}{9500}\right)^2$$

where E_v is measured in μv/m and R in km.

TABLE 4. Lava-Bed Antenna Efficiency

Antenna	f(kc)	σ (Measured $\mho$/m)	η (percent)
Desert Floor: 2 km length, 10 conductors, center fed, h = 0.15 m	30.5	1.6×10^{-2}	0.0023
Desert Lava Bed: 4.4 km length, 5 conductors, end fed, h = 1.2 m	10.9	7×10^{-4}	0.031
	20.6	8×10^{-4}	0.15
	32.7	9×10^{-4}	0.35
Hawaiian: 10 km length, 6 conductors, center fed, h = 0	10.9	4×10^{-4}	0.225
	20.6	4.3×10^{-4}	1.42
	32.7	4.8×10^{-4}	5.09
Sierra Nevadas: 10 km length, 6 conductors, center fed, h = 0	10.9	0.79×10^{-4}	1.14
	20.6	1.10×10^{-4}	5.55
	32.7	1.37×10^{-4}	17.80

The Hawaiian Island dipole is being built for use in the VLF propagation study program when 10 frequencies over the VLF band will be transmitted almost simultaneously. The increase in efficiency of this and the antenna in the Sierra Nevada Mountains near Courtright Lake (east of Fresno, California) is attributed to the lower soil conductivity (σ) and the longer antenna lengths, as compared with the lava-bed measurements.

IMPROVEMENT OF ANTENNA BANDWIDTH AND EFFICIENCY

In addition to locating the antenna over an area of the lowest possible soil conductivity and terminating it in its characteristic impedance for broad bandwidth, other methods are available for improving its efficiency.

PARALLEL CONDUCTORS

For a given input power, the antenna current can be increased only by lowering the input impedance—in this case, the antenna's characteristic impedance Z_o. This can be accomplished effectively by using parallel conductors, but only if the spacing between the conductors is sufficient to minimize mutual resistance. At VLF, this spacing is 100 to 1000 ft, depending upon soil conductivity—the lower the σ, the greater must be the spacing to maintain Z_m below a few ohms/km. When the conductor is elevated slightly, Z_m is greatly reduced (Fig. 5).

MULTIPLE CONDUCTORS

The advantage of using multiple parallel conductors is shown in Fig. 8, which shows the input impedance Z_{in} of a single conductor compared with that of five conductors. The Z_{in} of the latter is one-fifth that of the single conductor. Measurements showed that the radiated field strength of five conductors at 123 km range was five times that of the single conductor, with the same input power. Although increasing the number of conductors increases the antenna efficiency, diminishing returns may be expected when using more than 10 conductors because of the large amount of wire required.

GROUND-LEVEL CONDUCTOR

Another method of increasing antenna efficiency is to lay the conductor along the ground—thereby increasing the conductor-to-ground capacitance and lowering the Z_o. In an experiment with a single conductor 4.4 km long laid on the lava bed, the radiation efficiency at 30 kc was one and one-half times greater than when the conductor was elevated 4 ft. For the latter, the 500 Ω Z_o was more than one and one-half times the 320 Ω Z_o of the conductor on the ground.

The current attenuation is greater when the antenna is on the ground; however, for an antenna 4 to 5 km in length the efficiency increase resulting from the lower Z_o is much greater than the efficiency loss caused by the lowering of the average antenna current. For very long conductors, a limit to the gain in efficiency of the ground-level antenna is reached at the high end of the VLF band. In any case, the antenna usually must be elevated to prevent animals from damaging the conductors.

CAPACITANCE LOADING

Another method of increasing efficiency is by loading the conductor with capacitors in series; because

$$Z_o = \sqrt{\frac{L}{C}}$$

this will reduce conductor inductance and lower Z_o. Although this method has not been investigated fully, it is likely that the limiting factor may be a reduction in bandwidth.

Large bandwidth possibly may be obtained by the stagger-tuning of multiconductor dipoles of varied lengths. However, in locations where the soil conductivity is very low, it may be difficult to ground the antenna in its characteristic impedance.

CONCLUSIONS

The horizontal dipole, with modifications recommended in this report, is a useful VLF transmitting antenna for research in ionospheric physics, world-wide navigation systems, world-wide time standard system, and the like. Such an antenna is easily constructed and can be made very broad-band and reasonably efficient.

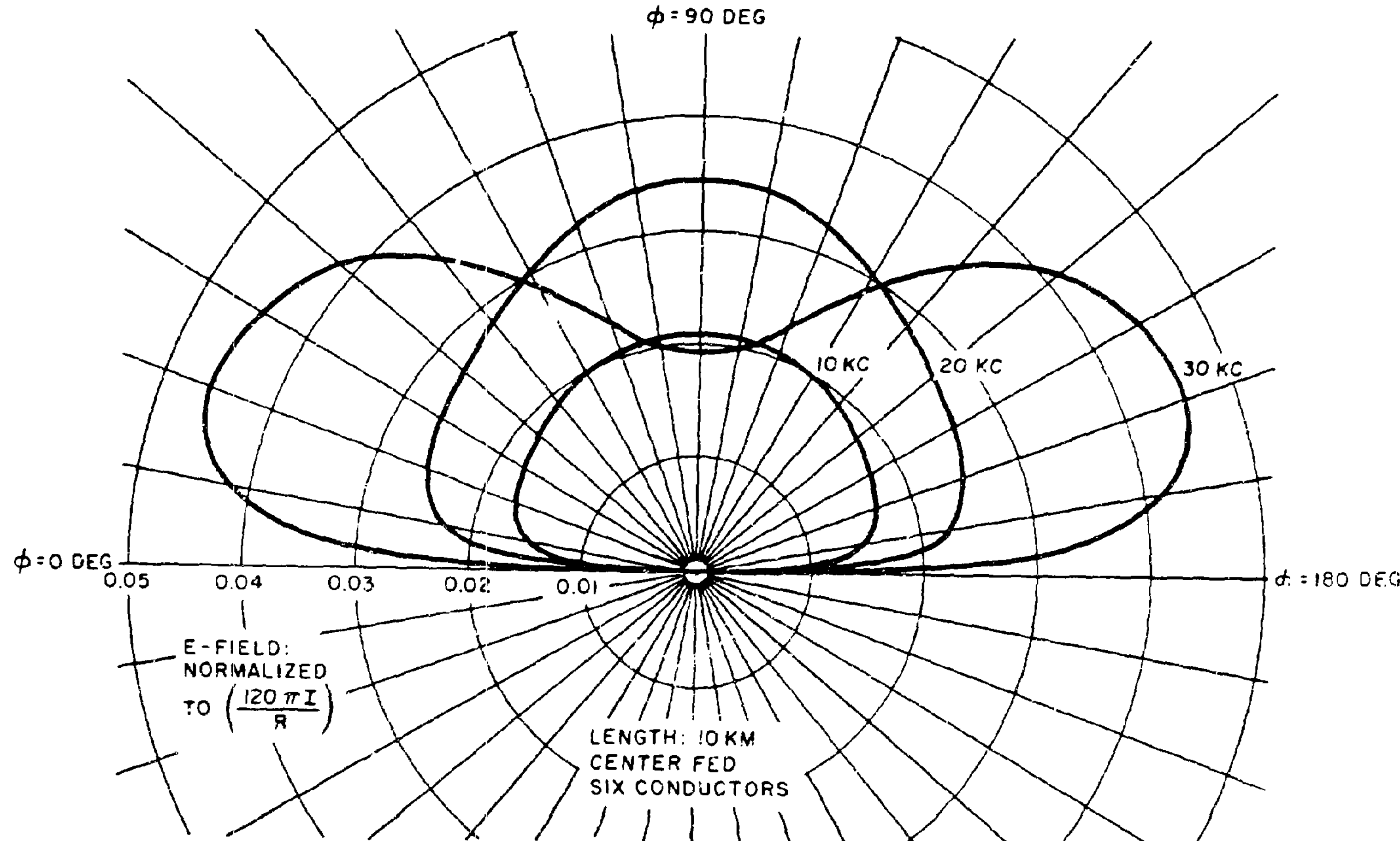

FIGURE 1. Elevation Pattern for Hawaiian Island Dipole

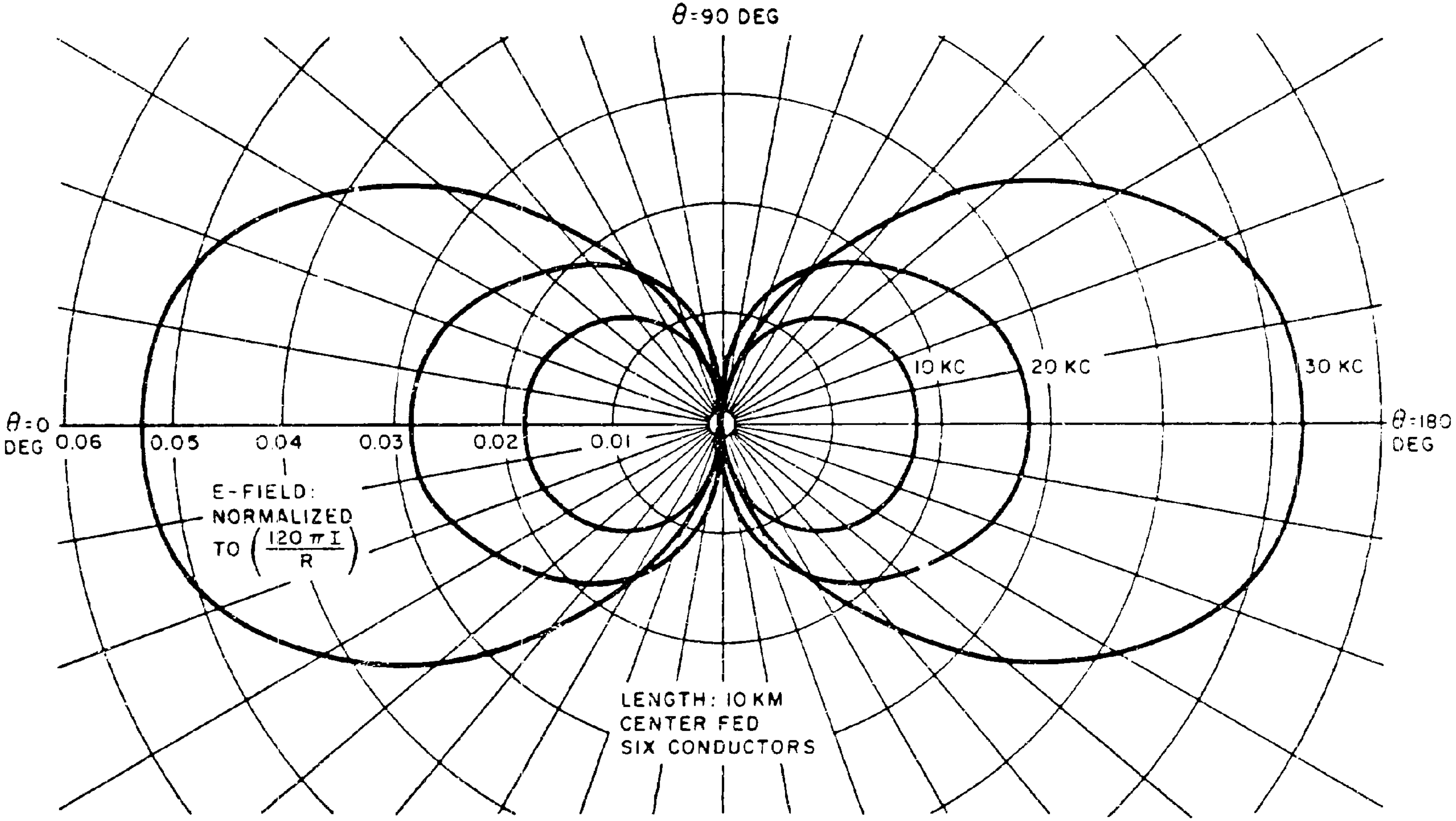

FIGURE 2. Azimuth Pattern for Hawaiian Island Dipole

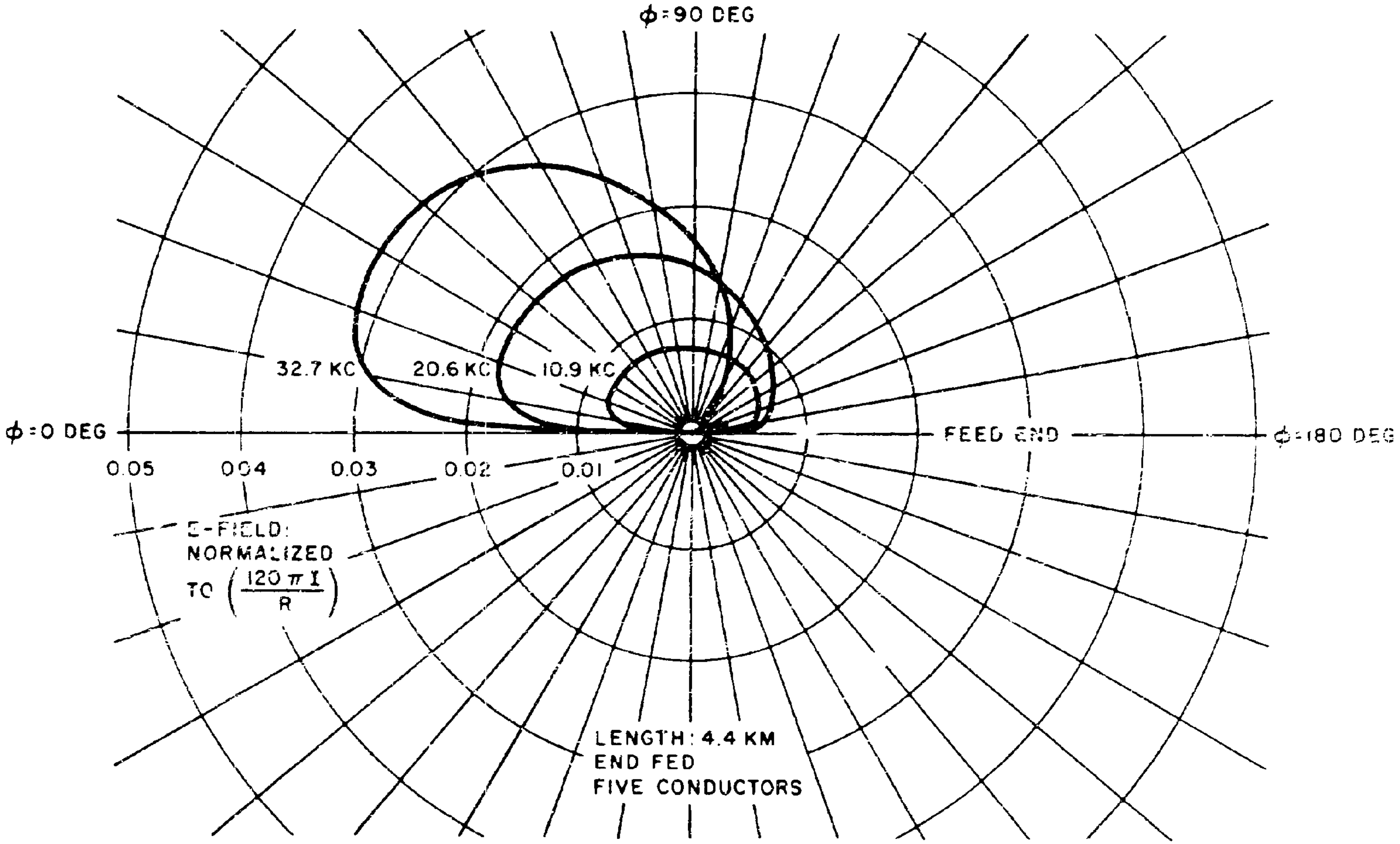

FIGURE 3. Elevation Pattern for Lava-Bed Antenna

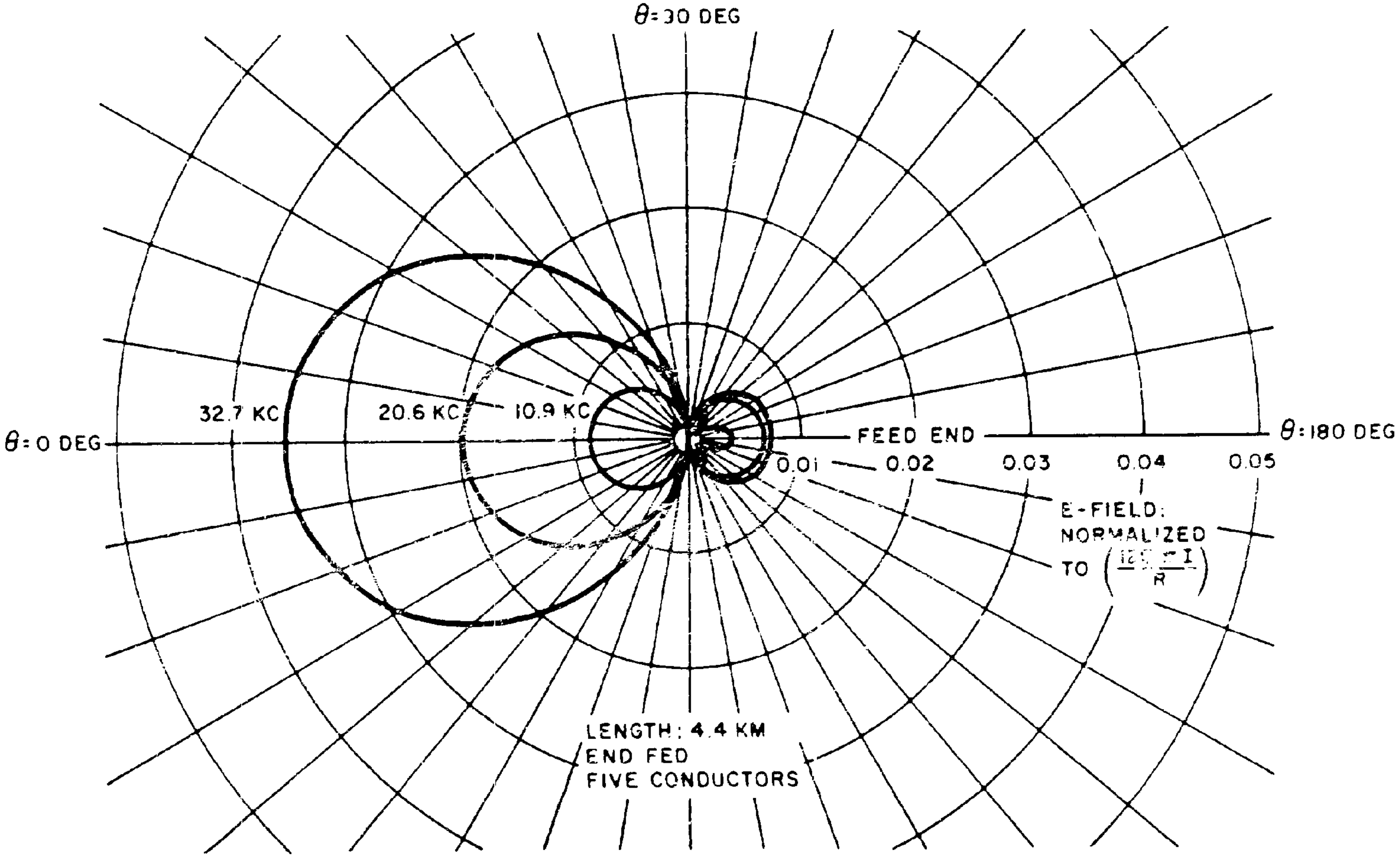

FIGURE 4. Azimuth Pattern for Lava-Bed Antenna

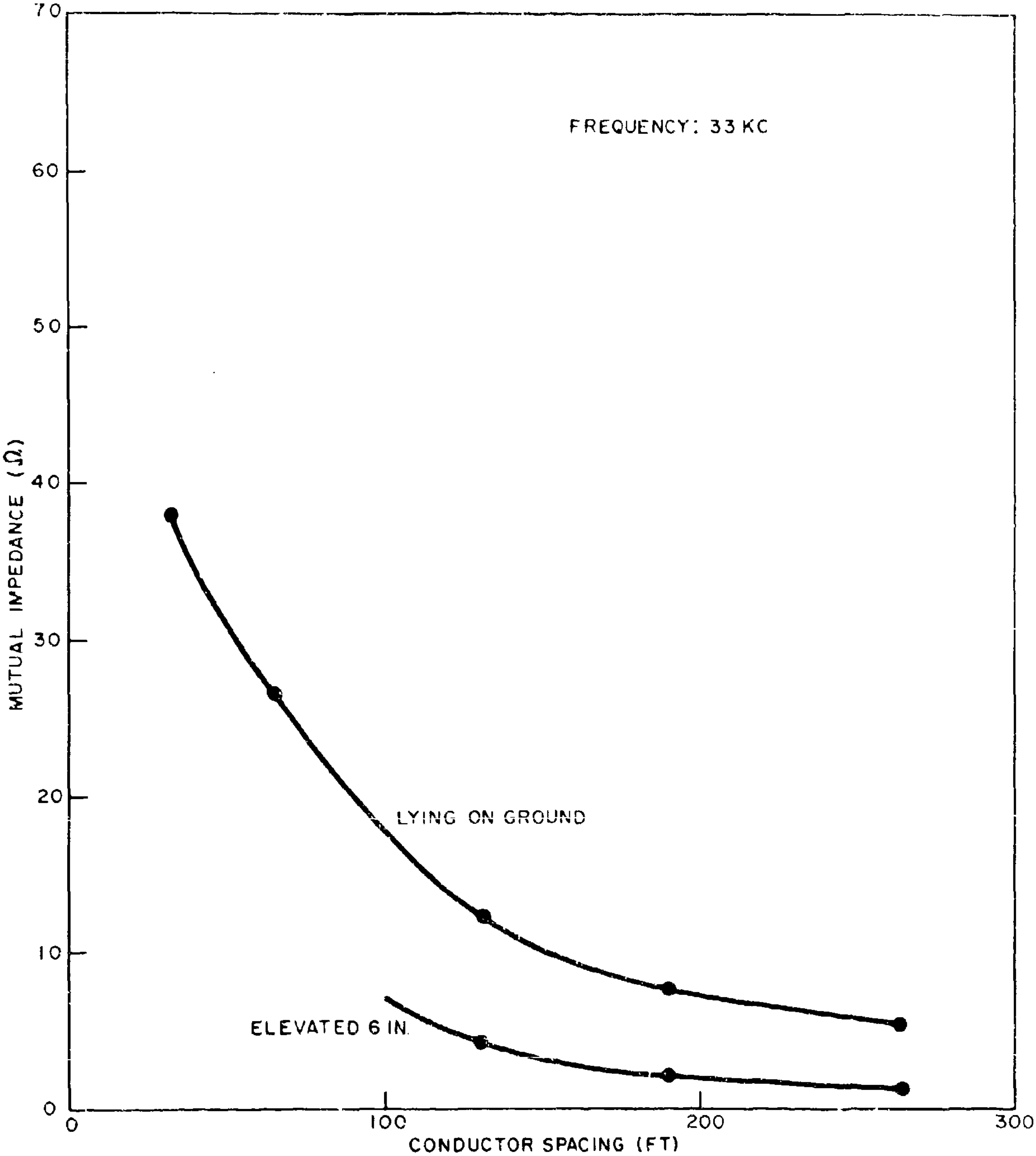

FIGURE 5. Mutual Impedance of Two-Conductor Dipole

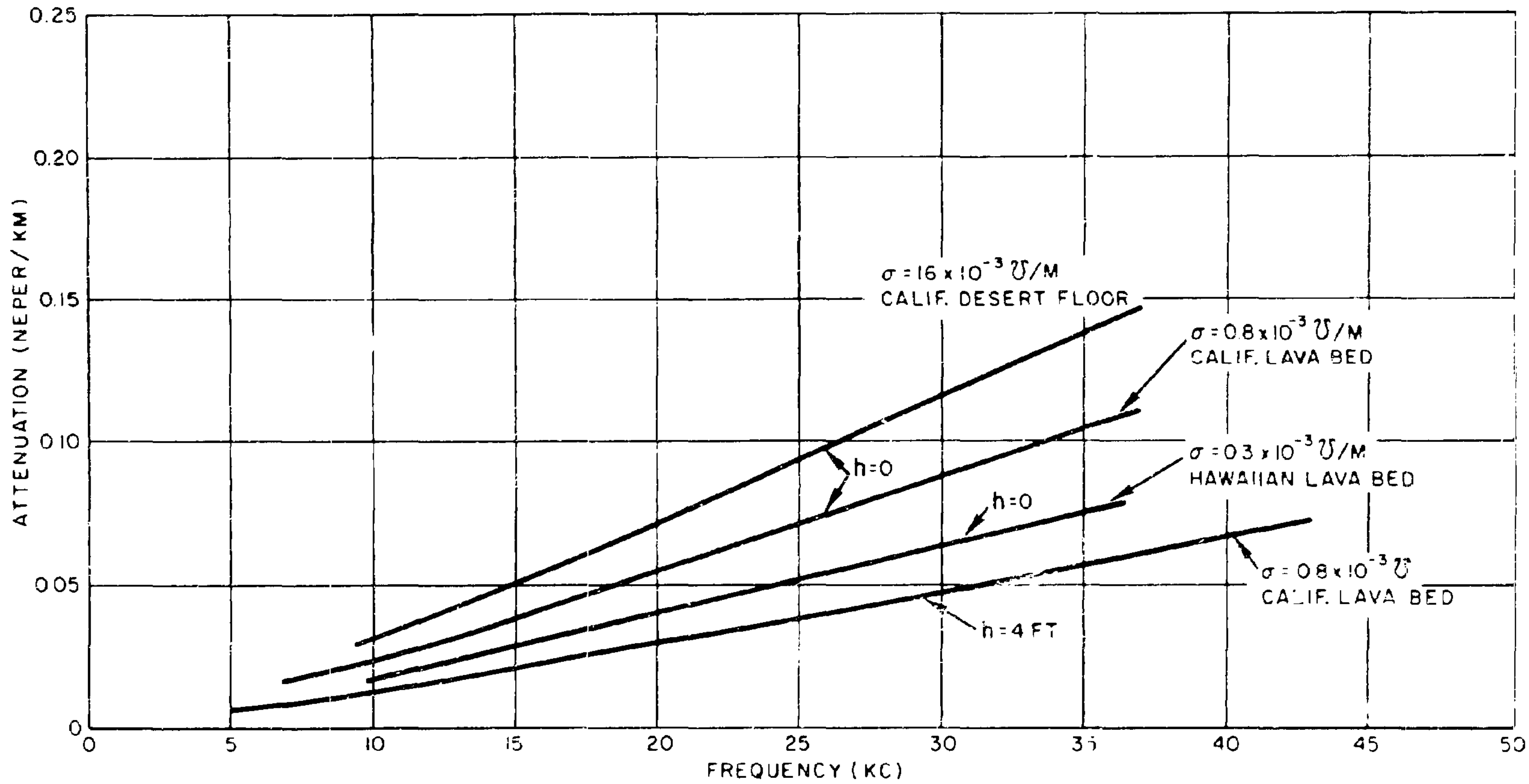

FIGURE 6. Horizontal Conductor Attenuation

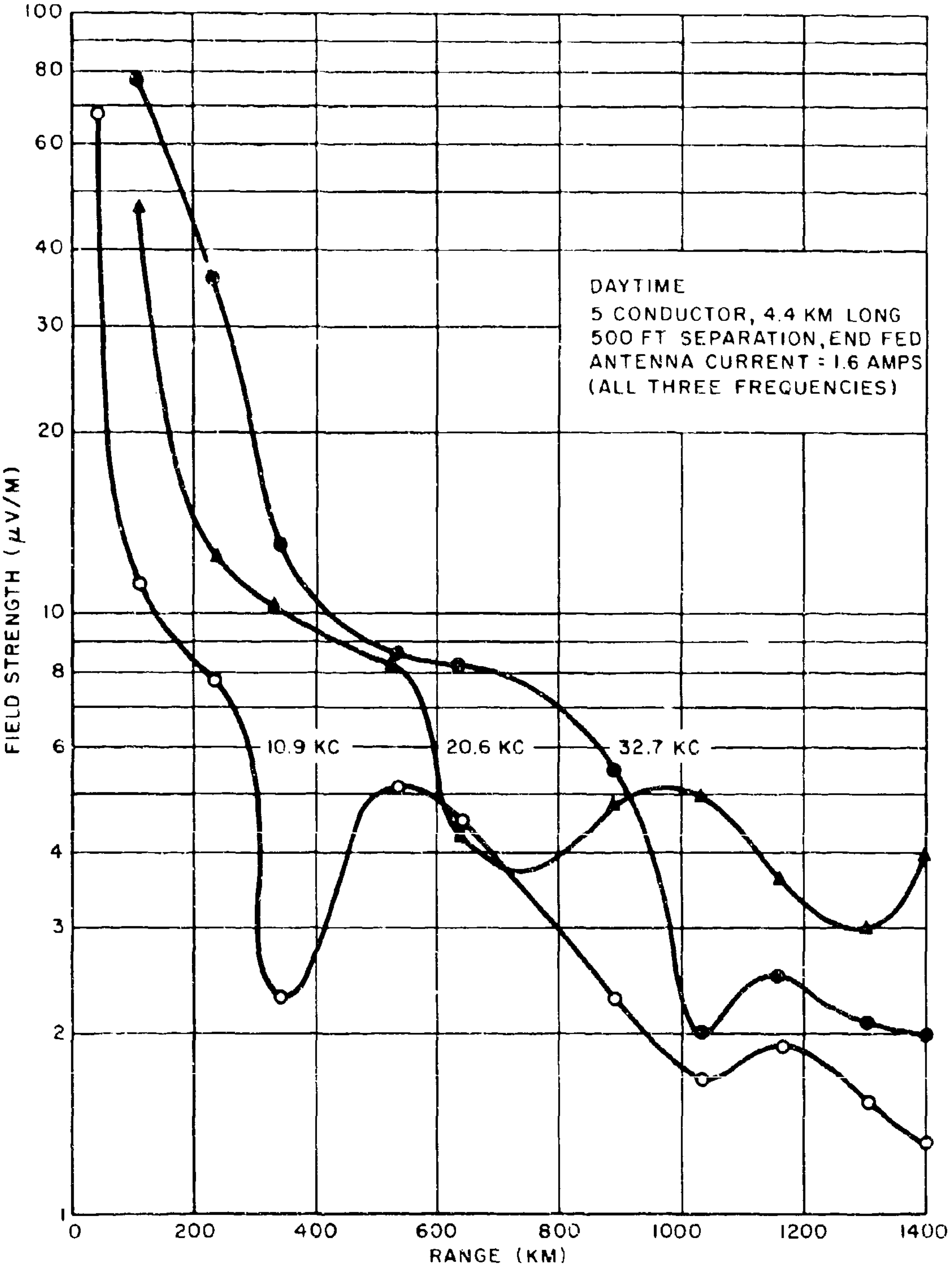

FIGURE 7. Propagated Field Strength of Lava-Bed Antenna

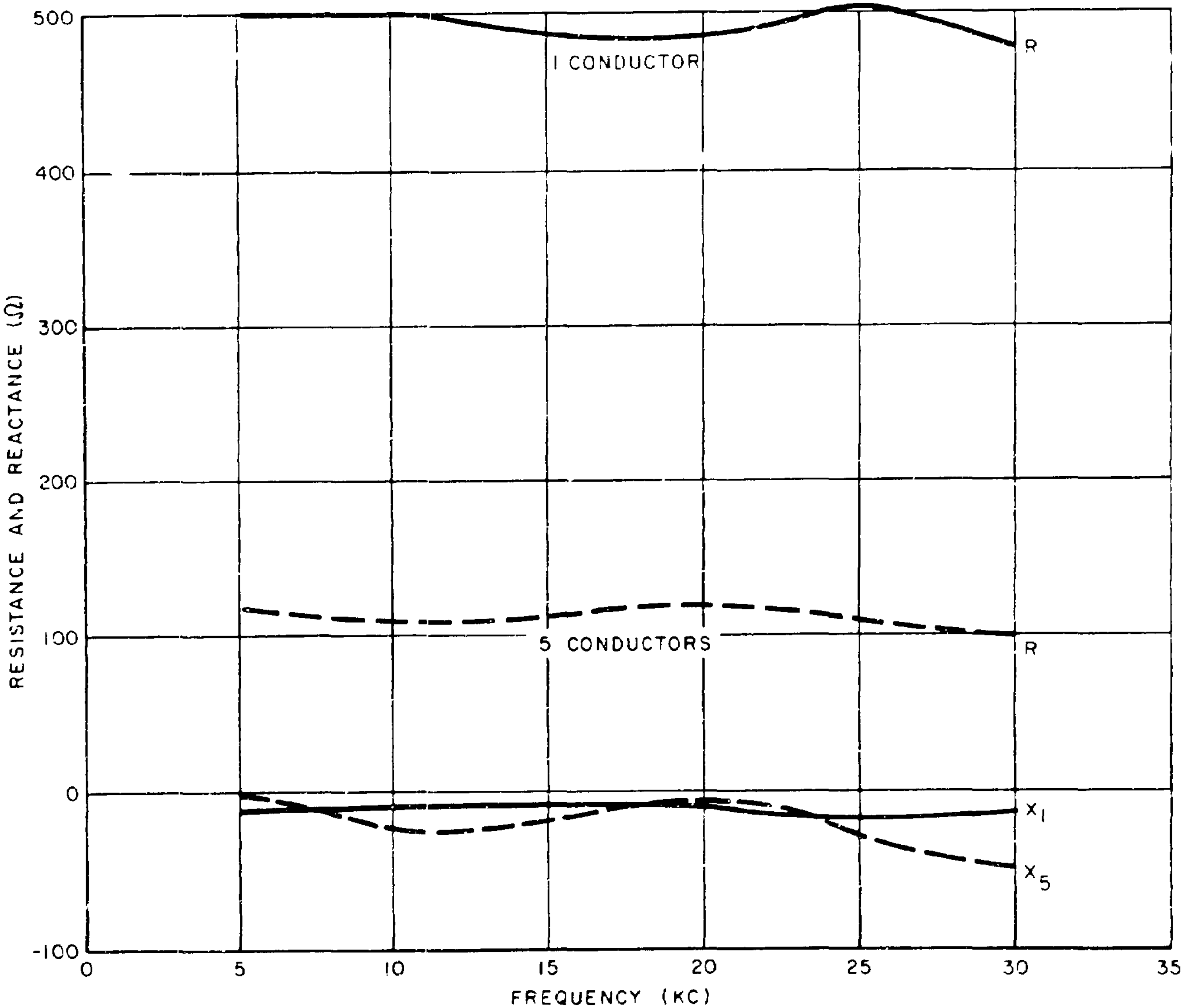

FIGURE 8. Resistance and Reactance of Lava-Bed Antenna

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13 ABSTRACT

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